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## Report Title

A New Non-Incremental Finite Element Solution Procedure for Rotor Dynamics

## ABSTRACT

The goal of this research project was to explore the use of a new finite element procedure in the analysis of rotor blades. The use of the large deformation finite element absolute nodal coordinate formulation in the analysis of rotating blades was examined, several important problems were identified and solved, and new challenges are encountered and discussed in this report. The developments made in this research project include introducing new reduced order thin beam and plate elements, improvements of the performance of existing full parameterized elements using different methods for formulating the elastic forces, implementation of the proposed formulations, formulation and implementation of new types of joints that are used in rotor blade models, and comparing the results of the eigenvalue analysis with existing finite element formulations. The challenges encountered during the course of this project and are still subject of our research are summarized in the following section.

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## List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

1. Dufva, K., and Shabana, A.A., “Analysis of Thin Plate Structure Using the Absolute Nodal Coordinate Formulation”, IMechE Journal of Multi-body Dynamics, accepted for publication.

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**Number of Papers published in peer-reviewed journals:** 2.00

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1. Hiroyuki Sugiyama (50%)

**Number of Graduate Students supported:** 1.00

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## List of faculty supported by the grant that are National Academy Members

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**FINAL REPORT**

# A NEW NON-INCREMENTAL FINITE ELEMENT SOLUTION PROCEDURE FOR ROTOR DYNAMICS

Proposal Number 47592-EG

Prepared by

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## INTRODUCTION

The goal of this research project was to explore the use of a new finite element procedure in the analysis of rotor blades. The use of the large deformation finite element absolute nodal coordinate formulation in the analysis of rotating blades was examined, several important problems were identified and solved, and new challenges are encountered and discussed in this report. The new finite element absolute nodal coordinate formulation is conceptually different from both the floating frame of reference formulation and large rotation vector formulations that have been extensively used in rotorcraft dynamics. The goal was to develop new beam and plate elements that can be efficiently used in rotorcraft applications. Specifically, the main objectives of this project are:

1. Development of new plate and beam elements based on the absolute nodal coordinate formulation which are suited for thin flexible blades.

2. Implement the new elements in a general purpose multi-body computer algorithm. Cholesky coordinates will be used instead of the element nodal coordinates in order to obtain an optimum sparse matrix structure.

3. Implement an aerodynamic model to study the coupling between the aerodynamic forces and the blade structural flexibility predicted using the absolute nodal coordinate formulation.

4. Compare the results obtained using the absolute nodal coordinate formulation with the results obtained by the research group at Georgia Tec. DYMORE is a finite element based multi-body dynamics code for the comprehensive modeling of rotorcraft systems developed at Georgia Tech under the sponsorship of the National Rotorcraft Technology Center. The goal here is to compare the performance of these two formulations on realistic rotorcraft configurations. An ideal test bench for this evaluation would be to compare the prediction of the two codes with the experimental measurements obtained from the UH-60 flight test program.

## ACCOMPLISMENTS AND CONTRIBUTIONS

During this Short Term Innovative Research Project (STIR), several important problems have been solved. The developments made in this research project include introducing new reduced order thin beam and plate elements, improvements of the performance of existing full parameterized elements using different methods for formulating the elastic forces, implementation of the proposed formulations, formulation and implementation of new types of joints that are used in rotor blade models, and comparing the results of the eigenvalue analysis with existing finite element formulations. The challenges encountered during the course of this project and are still subject of our research are summarized in the following section. The research groups at the University of Illinois at Chicago (UIC) and Georgia Tech plan to continue their collaboration in order to

successfully overcome these challenges. Specifically, the accomplishments made in and the contributions of this research project can be summarized as follows:

1. The performance of a thin plate element based on the absolute nodal coordinate formulation was investigated. A lower dimension plate element that allows for an arbitrary rigid body displacement as well as large deformation within the element was developed [1]. The element leads to a constant mass matrix and zero Coriolis and centrifugal forces. The performance of the element was compared with other plate elements previously developed using the absolute nodal coordinate formulation. As the result of eliminating the oscillations in some gradient components along the element thickness, it was shown that the finite element developed is much more efficient as compared to previously proposed elements in the case of thin structures, and in some applications the thin element models can be hundred times faster than the elements that employ full parameterization. Numerical examples were obtained in order to demonstrate the use of the formulation developed and the computational advantages gained from using the thin plate elements. The results of this investigation are reported in [1].

2. Several formulations for beam elements based on the absolute nodal coordinate formulation that can be effectively and efficiently used in the case of thin structural applications were developed. The numerically stiff behaviour resulting from shear terms in existing absolute nodal coordinate formulation beam elements that employ the continuum mechanics approach to formulate the elastic forces and the resulting locking phenomenon make these elements less attractive for slender stiff structures. In this project, additional shape functions are introduced for an existing spatial absolute nodal coordinate formulation beam element in order to obtain higher accuracy when the continuum mechanics approach is used to formulate the elastic forces. For thin structures where bending stiffness can be important, a lower order cable element is introduced and the performance of this cable element is evaluated by comparing it with existing formulations using several examples. Cables that experience low tension or catenary systems where bending stiffness has an effect on the wave propagation are examples in which the low order cable element can be used. The numerical study performed in this project shows that the use of existing implicit time integration methods enables the simulation of multibody systems with a moderate number of thin and stiff finite elements in reasonable CPU time [2].

3. Our research has been also focused on improving the performance of the full parameterized beam elements that allow for the deformation of the element cross section. In order to overcome the problem of high stiffness associated with some modes of deformations, the Hellinger-Reisner principle as proposed by Schwab was implemented [3]. Using this principle, a different interpolation for the shear stresses is used. The use of this approach led to significant improvements in the performance of the two- and three-dimensional full parameterized beam elements. The Hellinger-Reisner principle was implemented in a general multibody system

algorithm and used to test several examples. The results of this study will be documented in [4].

4. The new beam and plate finite elements developed in this research program have been implemented in a general flexible multibody algorithm that allows the simulation of rotating blades systematically and efficiently. The implementation allows for studying blades with arbitrary configurations and loading conditions. In the algorithm used in this investigation, all the new elements have a constant mass matrix, and therefore, Cholesky coordinates are used in order to obtain an optimum sparse matrix structure based on a generalized identity inertia matrix associated with the absolute nodal coordinates.

5. The rotor blade model developed at Georgia Tech includes rigid and spherical joints that can involve rigid, flexible and very flexible bodies. Some of these joints such as the rigid joint require introducing a tangent frame at the joint definition points in order to be able to impose constraints on the rotations at the joint nodes. Before the beginning of this project, these joint types were not formulated for thin elements. For example, reduced order thin plate elements that do not employ full parameterization require special treatment since one gradient vector is not readily available. This problem has been solved during the course of this project and the required joints were formulated, implemented in a multibody system algorithm and tested.

6. The groups at Georgia Tech and UIC identified the eignevalue solution as an important area for comparing the results of the two codes used at the two institutions. The eigenvalue capabilities in the code used at UIC were not designed to work for problems that have components modeled using the absolute nodal coordinate formulation. In the state space formulation used to solve for the general eigenvalue problem, the stiffness matrix is evaluated using numerical differentiation. When the absolute nodal coordinate formulation is used with a general continuum mechanics approach, the numerical differentiation results were not accurate for the eigenvalue solution. This problem was solved by using new methods for formulating the elastic forces. The results obtained for the eignevalue analysis for the absolute nodal coordinate formulation models were compared with the results obtained using existing finite element formulations. The comparison showed excellent agreement between the results of the two methods [5].

## CHALLENGES

While several important problems have been identified and solved in the STIR research program, the work on some other problems is still in progress. The remaining problems to be solved as well as the challenges encountered in this research project can be summarized as follows:

1. Georgia Tech provided the data file for the aerodynamic forces to UIC. The aerodynamic force model is currently being implemented in the UIC code. The completion of this job is expected in January. The results of the dynamic simulation and the comparison with the results obtained using the Georgia Tech model will be reported in [5]. A copy of this report will be sent to the Army Research Office.

2. One of the main challenges encountered in this research project was extracting the dimensions and material properties from the data received from Georgia Tech. These data which were provided to Georgia Tech by the industry assume that the cross section of the blade is rigid. Equivalent inertia and stiffness parameters were provided. Extracting reasonable equivalent dimensions and material properties from these data was very difficult and led to model and eigenvalue results which were not in a good agreement with the eigenvalue results obtained by Georgia Tech. Since the UIC eigenvalue results agree well with other existing finite element formulations, the discrepancy between the Georgia Tech and UIC results are attributed to differences in the models used. UIC could not get more specific information on the blade dimension because such information is proprietary. If one of the ARO laboratories has the dimensions for a rotor blade that are in open domain, Georgia Tech and UIC can use this blade model. Georgia Tech and UIC agreed to continue their collaboration in order to solve this problem. The results of their study will be reported in [5] and will be presented to ARO upon completion.

## REFERENCES

1. Dufva, K., and Shabana, A.A., “Analysis of Thin Plate Structure Using the Absolute Nodal Coordinate Formulation”, *IMechE Journal of Multi-body Dynamics*, accepted for publication.

2. Gerstmayr, J., and Shabana, A.A., “Analysis of Thin Beams and Cables Using the Absolute Nodal Coordinate Formulation”, *Nonlinear Dynamics*, accepted for publication.

3. Schwab, A.L., and Meijaard, “Comparison of Three-Dimensional Flexible Beam Element for Dynamic Analysis: Finite Element Method and Absolute Nodal Coordinate Formulation”, Proceedings of IDETC/CIE 2005, ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Paper # DETC2005-85104, September 24-28, 2005, Long Beach, California.

4. Hussien, B., Sugiyama, H., and Shabana, A., “Improvement of the Performance of the Full Parameterized Beam Elements Based on the Absolute Nodal Coordinate Formulation”, in preparation.

5. Maqueda, L., Shabana, A., Bauchau, O., “A New Finite Element Procedure for the Analysis of Rotor Blades”, in preparation.